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Supersymmetric Electroweak Parity Nonconservation in Top Quark Pair Production at the Fermilab Tevatron

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ABSTRACT

We evaluate the supersymmetric (SUSY) electroweak corrections to the effect of parity nonconservation in $q\bar{q} \rightarrow t\bar{t}$ production at the Fermilab Tevatron predicted by the Minimal Supersymmetric Model (MSSM). We find that the parity nonconserving asymmetry from the SUSY electroweak and SUSY Yukawa loop corrections predicted by the minimal supergravity (mSUGRA) model and the MSSM models with scenarios motivated by current data is about one percent. It will be challenging to observe such a small asymmetry at the Tevatron with 10 fb^{-1} of luminosity. It could however be observable if both the top- and bottom-squarks are light and $\tan\beta$ is smaller than 1, though these parameters are not favored by mSUGRA.

1 Introduction

Because of its large mass, $m_t = 175 \pm 6 \text{ GeV}$ [1], the lifetime of the top quark [$\sim (1.5 \text{ GeV})^{-1}$] is shorter than the time [$\sim (0.2 \text{ GeV})^{-1}$] needed to flip its spin. Hence, it is possible to study the polarization of this bare quark from its weak decay [2]. Using this unique property of the top quark, it was suggested in Ref. [3] that the asymmetry (denoted as \mathcal{A}) in the production rates of left-handed and right-handed top quarks observed at the Tevatron could be a good observable for probing physics that induces parity nonconserving effects.

Because QCD is C (charge conjugation) and P (parity) invariant, the single particle polarization of the top quark has to vanish for the QCD process $q\bar{q}, gg \rightarrow t\bar{t}$,¹ but can be nonvanishing if weak effects are present in their production. The contribution of the Born level electroweak reaction $q\bar{q} \rightarrow (\gamma, Z) \rightarrow t\bar{t}$ to the total cross section for the production of $t\bar{t}$ pairs is small (at the percent level for the Tevatron), so any spin effects present in $q\bar{q} \rightarrow (\gamma, Z) \rightarrow t\bar{t}$ are diluted by the QCD production of $t\bar{t}$ pairs. Considering the larger rate for the QCD production of $t\bar{t}$ pairs, similar spin effects that appear when considering the degree of polarization due to the weak corrections to $q\bar{q} \rightarrow g \rightarrow t\bar{t}$ at the loop level can be more significant. It was found in Refs. [3] and [5] that the effect from the Standard Model (SM) weak corrections to this asymmetry is typically less than a fraction of percent. It increases as the invariant mass ($M_{t\bar{t}}$) of the $t\bar{t}$ pair increases and reaches about 0.4% for $M_{t\bar{t}} > 500 \text{ GeV}$ and about 1% at the TeV region.

Because the SM contribution is small, this asymmetry may provide a good probe for new physics beyond the SM. One of the candidates for new physics consistent with current low energy data (including Z -pole physics) is the Minimal Supersymmetric Standard Model (MSSM) [6]. Recently in the context of the MSSM the effect of Yukawa contributions from the Higgs sector to this asymmetry \mathcal{A} in the $q\bar{q} \rightarrow t\bar{t}$ process was evaluated and found to be of the same size as the SM effect for $\tan \beta \equiv v_2/v_1 < \sqrt{m_t/m_b}$ and enhanced by about a factor of 2 for $\tan \beta > m_t/m_b$ when the mass of the charged Higgs boson $m_{H^\pm} < 300 \text{ GeV}$ [5]. However, in the MSSM, in addition to the Yukawa contributions from the Higgs sector, the genuine supersymmetric electroweak (SUSY EW) corrections from the spin-1/2 supersymmetric particles contributing in loops should also be considered. This is because in the

¹ Here, we shall not consider the degree of (transverse) polarization of the top quark in the direction that is perpendicular to the scattering plan of the $t\bar{t}$ pair production. This transverse polarization can be generated through loop effects from QCD interaction [4, 2].

SUSY models the loop contribution from spin-0 particles is often cancelled by that from spin-1/2 particles. A complete study of the parity nonconserving effect in top quark pair production from SUSY models should therefore include both the SUSY EW and SUSY Yukawa corrections.

In this work, we evaluate the genuine SUSY EW contribution of order $\alpha m_t^2/m_W^2$ to the parity nonconserving asymmetry \mathcal{A} in the $t\bar{t}$ pair productions at the Fermilab Tevatron. At the Tevatron, a $p\bar{p}$ collider with CM energy $\sqrt{s} = 2 \text{ TeV}$, the $t\bar{t}$ pairs are produced predominately via the QCD process $q\bar{q} \rightarrow t\bar{t}$; hence, we shall only consider the SUSY EW corrections for the $q\bar{q} \rightarrow t\bar{t}$ process. With a 2 fb^{-1} luminosity (expected at the Tevatron Run II), there will be about 1000 fully reconstructed $t\bar{t}$ pairs [7], which implies that it is possible to observe the parity nonconserving asymmetry of $\sim 3\%$ in magnitude. To probe physics that contributes to a smaller $|\mathcal{A}|$, a higher luminosity is needed. For completeness, we shall also give our results for an integrated luminosity of 10 fb^{-1} .

2 SUSY electroweak corrections

The genuine supersymmetric electroweak contribution of order $\alpha m_t^2/m_W^2$ to the amplitude of $q\bar{q} \rightarrow t\bar{t}$ is contained in the radiative corrections to the $t\bar{t}g$ vertex. The relevant Feynman diagrams were shown in Fig. 1 of Ref. [8], and the Feynman rules can be found in Ref. [6]. In our calculation, we used dimensional regularization to regulate all the ultraviolet divergences in the virtual loop corrections and we adopted the on-mass-shell renormalization scheme [9]. The renormalized $gt\bar{t}$ vertex is

$$-ig_s \bar{u}(p) T^a [\Gamma_0^\mu + \Gamma_1^\mu] v(q), \quad (1)$$

where p, q are the momenta of outgoing t quark and its antiparticle, $\Gamma_0^\mu = \gamma^\mu$ is the tree level vertex and Γ_1^μ is the one-loop vertex function which can be expressed in terms of form factors [2]

$$\begin{aligned} \Gamma_1^\mu &= \gamma^\mu [A(\hat{s}) - B(\hat{s})\gamma_5] \\ &\quad + (p - q)^\mu [C(\hat{s}) - D(\hat{s})\gamma_5] \\ &\quad + (p + q)^\mu [E(\hat{s}) - F(\hat{s})\gamma_5], \end{aligned} \quad (2)$$

where $\hat{s} = (p + q)^2$. If CP is conserved, then $D = 0$.² The conservation of the vector

² In the SM, this is the case when ignoring the CP violating phase in the Cabibbo-Kobayashi-Maskawa quark mixing matrix. In SUSY models, it is possible to have other CP violating sources, such as the trilinear term (A -term) in the Higgs potential. However, for simplicity, we shall not include them in this study.

current for the renormalized $gt\bar{t}$ vertex demands that $E = 0$ and $F(\hat{s}) = -2m_t B(\hat{s})/\hat{s}$.

The form factors from the supersymmetric electroweak corrections can be written as

$$\begin{aligned}
A &= \frac{g^2 m_t^2}{32\pi^2 m_W^2 \sin^2 \beta} (F_1 + 2m_t F_5), \\
B &= -\frac{g^2 m_t^2}{32\pi^2 m_W^2 \sin^2 \beta} F_2, \\
C &= -\frac{g^2 m_t^2}{32\pi^2 m_W^2 \sin^2 \beta} F_5, \\
D &= E = 0, \\
F &= -\frac{2m_t}{\hat{s}} B(\hat{s}),
\end{aligned} \tag{3}$$

where $F_{1,2,5}$ are defined as in Ref. [10] by

$$F_i = F_i^c + F_i^n, \tag{4}$$

and F_i^c and F_i^n are the loop contributions from diagrams involving charginos and neutralinos, respectively. Also [10],

$$\begin{aligned}
F_1^c &= \sum_{j=1,2} V_{j2} V_{j2}^* \left[c_{24} + m_t^2 (c_{11} + c_{21}) + \left(\frac{1}{2} B_1 + m_t^2 B_1' \right) (m_t, \tilde{M}_j, m_{\tilde{b}}) \right], \\
F_2^c &= \sum_{j=1,2} V_{j2} V_{j2}^* \left[c_{24} + \frac{1}{2} B_1 (m_t, \tilde{M}_j, m_{\tilde{b}}) \right], \\
F_5^c &= -\frac{1}{2} m_t \sum_{j=1,2} V_{j2} V_{j2}^* (c_{11} + c_{21}),
\end{aligned} \tag{5}$$

In the above results, the scalar functions $c_{ij}(-p_3, p_3 + p_4, \tilde{M}_j, m_{\tilde{b}}, m_{\tilde{b}})$ and B_1 are the usual 3-point and 2-point Feynman integrals, respectively [11]. The chargino masses \tilde{M}_j and the mixing matrix elements V_{ij} depend on the SUSY parameters M_2 , μ , and $\tan \beta$ [6]. Furthermore, $B'_{0,1}$ are defined by

$$B'_{0,1}(m, m_1, m_2) = \frac{\partial B_{0,1}(p, m_1, m_2)}{\partial p^2} \Big|_{p^2=m^2}. \tag{6}$$

In Eq. (4), F_i^n can be written as

$$F_i^n = F_i^{\tilde{t}_1} + F_i^{\tilde{t}_2} + F_i^s, \tag{7}$$

where F_1^s and F_2^s are given by

$$F_1^s = \sum_{j=1}^4 \left\{ \frac{1}{2} N_{j4} N_{j4}^* \left[B_1(m_t, \tilde{M}_{0j}, m_{\tilde{t}_1}) + B_1(m_t, \tilde{M}_{0j}, m_{\tilde{t}_2}) \right] \right\}$$

$$\begin{aligned}
& +m_t^2 N_{j4} N_{j4}^* \left[B_1'(m_t, \tilde{M}_{0j}, m_{\tilde{t}_1}) + B_1'(m_t, \tilde{M}_{0j}, m_{\tilde{t}_2}) \right] \\
& +m_t \tilde{M}_{0j} N_{j4} N_{j4} \sin(2\theta_t) \left[B_0'(m_t, \tilde{M}_{0j}, m_{\tilde{t}_2}) - B_0'(m_t, \tilde{M}_{0j}, m_{\tilde{t}_1}) \right] \Big\}, \\
F_2^s &= \sum_{j=1}^4 \frac{1}{2} N_{j4} N_{j4}^* \cos(2\theta_t) \left[B_1(m_t, \tilde{M}_{0j}, m_{\tilde{t}_1}) - B_1(m_t, \tilde{M}_{0j}, m_{\tilde{t}_2}) \right] \\
F_5^s &= 0,
\end{aligned} \tag{8}$$

and $F_i^{\tilde{t}_1}$ are given by

$$\begin{aligned}
F_1^{\tilde{t}_1} &= \sum_{j=1}^4 \left\{ N_{j4} N_{j4}^* \left[c_{24} + m_t^2 (c_{11} + c_{21}) \right] - \sin(2\theta_t) N_{j4} N_{j4} m_t \tilde{M}_{0j} (c_0 + c_{11}) \right\}, \\
F_2^{\tilde{t}_1} &= \sum_{j=1}^4 N_{j4} N_{j4}^* c_{24} \cos(2\theta_t), \\
F_5^{\tilde{t}_1} &= \sum_{j=1}^4 \left[-\frac{1}{2} m_t N_{j4} N_{j4}^* (c_{11} + c_{21}) + \frac{1}{2} \sin(2\theta_t) N_{j4} N_{j4} \tilde{M}_{0j} (c_0 + c_{11}) \right],
\end{aligned} \tag{9}$$

where $c_{ij}(-p_3, p_3 + p_4, \tilde{M}_{0j}, m_{\tilde{t}_1}, m_{\tilde{t}_1})$ and c_0 are the 3-point Feynman integrals [11]. The neutralino masses \tilde{M}_{0j} and the mixing matrix elements N_{ij} are obtained by diagonalizing the neutralino mass matrix Y [6] which depends on the SUSY parameters M_1 , M_2 , μ and $\tan\beta$. Here, μ is the coefficient of the $H_1 H_2$ mixing term in the superpotential and M_2, M_1 are the $SU(2)$ and the $U(1)$ gaugino masses, respectively. In general, the mass matrix of top-squarks takes the form [12]

$$\mathcal{M}_t^2 = \begin{pmatrix} m_{\tilde{t}_L}^2 & m_t M_{LR} \\ m_t M_{LR} & m_{\tilde{t}_R}^2 \end{pmatrix}, \tag{10}$$

where $M_{\tilde{t}_L}^2, M_{\tilde{t}_R}^2$ are the soft SUSY-breaking mass terms for left- and right-handed top-squarks, and $M_{LR} = \mu \cot\beta + A_t$, with A_t being the coefficient of the trilinear soft SUSY-breaking term $\tilde{t}_L \tilde{t}_R H_2$. The mass eigenstates of the top-squarks $\tilde{t}_{1,2}$ are related to $\tilde{t}_{L,R}$ by $\tilde{t}_1 = \cos\theta_t \tilde{t}_L + \sin\theta_t \tilde{t}_R$, and $\tilde{t}_2 = -\sin\theta_t \tilde{t}_L + \cos\theta_t \tilde{t}_R$, where θ_t is the mixing angle of the top-squarks.

The form factors $F_i^{\tilde{t}_2}$ can be obtained from $F_i^{\tilde{t}_1}$ by a proper transformation, and

$$F_i^{\tilde{t}_2} = F_i^{\tilde{t}_1} \Big|_{\sin(2\theta_t) \rightarrow -\sin(2\theta_t), \cos(2\theta_t) \rightarrow -\cos(2\theta_t), m_{\tilde{t}_1} \rightarrow m_{\tilde{t}_2}}. \tag{11}$$

In the next section, we will discuss the formalism for calculating the asymmetry \mathcal{A} which measures the degree of parity nonconservation in $t\bar{t}$ pairs produced at the Tevatron.

3 Asymmetry and parity nonconservation

Although a large part of this section is contained in Refs. [3] and [5], for completeness, we will briefly summarize the relevant results. Let us define the cross section for the subprocess $q\bar{q} \rightarrow t\bar{t}$ for definite helicity states of the $t\bar{t}$ pair to be

$$\hat{\sigma}_{\lambda_1, \lambda_2} \equiv \hat{\sigma}(q\bar{q} \rightarrow t_{\lambda_1} \bar{t}_{\lambda_2}), \quad (12)$$

where $\lambda_{1,2}$ designates right-handed (R) or left-handed (L) helicity.

At the tree level,

$$\begin{aligned} \hat{\sigma}_{LL}^{(0)} &= \hat{\sigma}_{RR}^{(0)} = \frac{4\pi\alpha_s^2\beta}{27\hat{s}^2}(2m_t^2), \\ \hat{\sigma}_{LR}^{(0)} &= \hat{\sigma}_{RL}^{(0)} = \frac{4\pi\alpha_s^2\beta}{27\hat{s}^2}(\hat{s}), \\ \hat{\sigma}^{(0)} &= \hat{\sigma}_{LL}^{(0)} + \hat{\sigma}_{RR}^{(0)} + \hat{\sigma}_{LR}^{(0)} + \hat{\sigma}_{RL}^{(0)} = \frac{8\pi\alpha_s^2\beta}{27\hat{s}}(1 + 2m_t/\hat{s}), \end{aligned} \quad (13)$$

after properly including the spin and color factors.

With one loop radiative corrections the cross section for each helicity state of the $t\bar{t}$ pair is $\hat{\sigma}_{\lambda_1, \lambda_2} = \hat{\sigma}_{\lambda_1, \lambda_2}^{(0)} + \delta\hat{\sigma}_{\lambda_1, \lambda_2}$, where $\delta\hat{\sigma}_{\lambda_1, \lambda_2}$ is the contribution from weak corrections. Defining a K -factor for each helicity state of the $t\bar{t}$ pair to be

$$K_{\lambda_1, \lambda_2} \equiv \frac{\hat{\sigma}_{\lambda_1, \lambda_2}}{\hat{\sigma}_{\lambda_1, \lambda_2}^{(0)}} = 1 + \frac{\delta\hat{\sigma}_{\lambda_1, \lambda_2}}{\hat{\sigma}_{\lambda_1, \lambda_2}^{(0)}}, \quad (14)$$

these K -factors are

$$\begin{aligned} K_{LL} &= 1 + 2\text{Re}(A) - \beta^2\hat{s}\text{Re}(C)/m_t + \beta\hat{s}\text{Re}(D)/m_t, \\ K_{RR} &= 1 + 2\text{Re}(A) - \beta^2\hat{s}\text{Re}(C)/m_t - \beta\hat{s}\text{Re}(D)/m_t, \\ K_{LR} &= 1 + 2\text{Re}(A) + 2\beta\text{Re}(B), \\ K_{RL} &= 1 + 2\text{Re}(A) - 2\beta\text{Re}(B), \end{aligned} \quad (15)$$

with $\beta = \sqrt{1 - 4m_t^2/\hat{s}}$. If CP is conserved, then $\text{Re}(D) = 0$ and $K_{LL} = K_{RR}$. Because $t_R\bar{t}_L$ is the conjugate state of $t_L\bar{t}_R$ under parity transformation, any difference in K_{RL} and K_{LR} implies a parity nonconserving interaction.

The cross section for $p\bar{p} \rightarrow t\bar{t} + X$ is evaluated by calculating the convolution of the constituent cross section $\hat{\sigma}(q\bar{q} \rightarrow t\bar{t})$ and parton distribution functions. The effects of parity nonconservation can appear as an asymmetry in the invariant mass ($M_{t\bar{t}}$) distributions as well as in the integrated cross sections for $t_R\bar{t}_L$ and $t_L\bar{t}_R$ productions.

Let us define the differential asymmetry to be

$$\begin{aligned}
\delta\mathcal{A}(M_{t\bar{t}}) &\equiv \frac{d\sigma_{RL}/dM_{t\bar{t}} - d\sigma_{LR}/dM_{t\bar{t}}}{d\sigma_{RL}/dM_{t\bar{t}} + d\sigma_{LR}/dM_{t\bar{t}}} \\
&= \frac{K_{RL} - K_{LR}}{K_{RL} + K_{LR}} \\
&= \frac{-2\beta\text{Re}(B)}{1 + 2\text{Re}(A)},
\end{aligned} \tag{16}$$

where the parton distribution functions cancel in this ratio.

Since the polarization of the top quark has to be deduced from the distributions of the decay products, such as b -jets and leptons, it is necessary to have a fully reconstructed $t\bar{t}$ event to determine the polarizations of both t and \bar{t} . To increase statistics we can sum over the helicities of the \bar{t} and consider an integrated asymmetry in the numbers of t_R and t_L produced. In this case, the number of observed $t\bar{t}$ events will be reduced by only the branching ratio for $t \rightarrow W^+b \rightarrow \ell^+\nu_\ell b$, where $\ell = e$ or μ . The integrated asymmetry, after integrating over a range of $M_{t\bar{t}}$, is then defined by

$$\mathcal{A} \equiv \frac{N_R - N_L}{N_R + N_L} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}, \tag{17}$$

where $\sigma_R = \sigma_{RL} + \sigma_{RR}$, $\sigma_L = \sigma_{LR} + \sigma_{LL}$, and N_R and N_L are the numbers of right-handed and left-handed top quarks which decay semileptonically.

4 Numerical results and conclusions

In our numerical calculations, to facilitate comparison with the effect from the SUSY Yukawa corrections evaluated in [5], we take the same values as those in Ref. [5] for the SM parameters. More precisely, we take $m_Z = 91.187$ GeV, $m_W = 80.22$ GeV, $m_b = 4.8$ GeV, $m_t = 170$ GeV, and $\sin^2\theta_W = 0.2319$. We also use the same parton distribution functions, CTEQ3L [13], to evaluate the cross section with the choice of scale $Q^2 = \hat{s} = M_{t\bar{t}}^2$. As to the SUSY parameters we shall consider two classes of models in order.

The currently most popular SUSY model is the minimum supergravity (mSUGRA) model [14] which only has four continuous and one discrete free parameters not present in the SM. At the unification scale M_X these are m_0 (common scalar mass), $m_{1/2}$ (common gaugino mass), A_0 (common trilinear scalar coupling), $\tan\beta$ (the ratio of vevs), and $\text{sign}(\mu)$. A common value $m_{1/2}$ at the scale M_X is motivated by the apparent unification of the measured gauge couplings within the MSSM at the scale

$M_X \simeq 2 \times 10^{16}$ GeV. Through the renormalization group equations of the mSUGRA model, the gaugino masses M_1 and M_2 are related by $M_1 = \frac{5}{3} \frac{g'^2}{g^2} M_2 \simeq 0.5 M_2$ at the electroweak scale. This model predicts radiative breaking of the electroweak gauge symmetry due to the large top quark mass. Consequently, it is possible to have large splitting in the masses of left-top squarks and right-top squarks, while the masses of all the other (left- or right-) squarks are about the same [15]. Because of the heavy top quark this model requires values of $\tan \beta$ to be larger than ~ 1 so that the top Yukawa coupling will not become exponentially large below the high energy scale M_X , especially since there is evidence that the gauge couplings are perturbative up to that scale. Similarly, $\tan \beta$ is required to be smaller than ~ 50 where the bottom and τ Yukawa couplings are likewise close to their perturbative limits [15].

Another type of SUSY model uses the full (> 100 parameters) parameter space freedom of the MSSM and fits the data, assuming one has a supersymmetry signal. This approach has been used in studying the CDF $e^-e^+\gamma\gamma + \cancel{E}_T$ event [16]. It was found that to also explain all the low energy data (including α_s , R_b and the branching ratio of $b \rightarrow s\gamma$, etc.), the lightest mass eigenstate (\tilde{t}_1) of top squarks is likely to be the right-stop (\tilde{t}_R) with a mass of the order of m_W ; the lightest neutralino ($\tilde{\chi}_1^0$) is Higgsino-like and the second lightest neutralino ($\tilde{\chi}_2^0$) is gaugino-like; $\tan \beta$ is of the order one; M_2 and M_1 are of the same order of magnitude as m_Z (the mass of Z -boson); the $\text{sign}(\mu)$ is negative; and $|\mu| \sim M_Z$ [16]. We shall refer to this class of models as MSSM models with scenarios motivated by current data.

The relevant SUSY parameters for our study are μ , $\tan \beta$, M_1 , M_2 (which determine couplings, masses and mixings of neutralinos and charginos), and the masses of the top- and bottom-squarks. When considering SUSY EW corrections, charginos and neutralinos will contribute only in loops and their contributions are generally small unless they are light. Likewise, only a light top-squark (or bottom-squark) can give large contributions to loop calculations. Since we are interested in contributions of the order m_t^2/v^2 , where v is the vacuum expectation value, only Higgsino components of the charginos and the neutralinos are relevant for our calculation. Because in the MSSM the top quark obtains its mass by interacting with the second Higgs doublet through Yukawa coupling, the coupling of Higgsino-top-stop is proportional to $m_t/v_2 = m_t/v \sin \beta$. Hence, we expect large parity nonconserving asymmetry occurs for small values of $\tan \beta$.

After sampling a range of values of SUSY parameters in the region that might give large contributions to the asymmetry \mathcal{A} , and which are also consistent with either of

the above two classes of models, we found that the asymmetry \mathcal{A} is generally small, less than a couple of percent in magnitude, though it can be either positive or negative depending on the values of the SUSY parameters. To illustrate the effects of SUSY EW corrections to the parity nonconserving observable \mathcal{A} , in Tables 1 and 2 we give a few representative sets of SUSY parameters and the corresponding asymmetries \mathcal{A}_{EW} (due to SUSY EW contributions) and/or \mathcal{A}_Y (due to SUSY Yukawa contributions). The relevant parameters used for calculating the results in Tables 1 and 2 are: $M_{t\bar{t}} > 500 \text{ GeV}$;³ $m_{\tilde{t}_1} = 50 \text{ GeV}$ or 90 GeV ; $m_{\tilde{t}_2} = m_{\tilde{b}_1} = m_{\tilde{b}_2} = 500 \text{ GeV}$; $m_{H^+} = 300 \text{ GeV}$, and $\mu = -60 \text{ GeV}$ or -90 GeV . In addition, we choose the SUSY parameter $A_t = -\mu \cot \beta$ (i.e. $M_{LR} = 0$) so that the mass eigenstates of the stops coincide with \tilde{t}_R and \tilde{t}_L up to a phase. Furthermore, we consider the case that $m_{\tilde{t}_R}$ is smaller than $m_{\tilde{t}_L}$, which corresponds to $\theta_t = \pi/2$. Accordingly, the mass eigenstates of the stops \tilde{t}_1 and \tilde{t}_2 are just \tilde{t}_R (a right-handed stop) and $-\tilde{t}_L$ (a left-handed stop), respectively. Using these values we calculated the results for a 2 TeV Tevatron with an integrated luminosity of 10 fb^{-1} . (The effect of parity nonconservation in the $t\bar{t}$ events is too small to be observable with only 2 fb^{-1} of luminosity.)

In Table 1, we show the parity nonconserving asymmetry \mathcal{A} from SUSY EW contributions. The representative results shown in this Table span the SUSY parameter space: $1 < \tan \beta < 3$, $50 \text{ GeV} < M_1 < 100 \text{ GeV}$, $50 \text{ GeV} < M_2 < 100 \text{ GeV}$, with $\mu = -60$ and $m_{\tilde{t}_1} = 50 \text{ GeV}$ or 90 GeV . It is clear that the values of $|\mathcal{A}_{EW}|$ can be of the same size for either $M_1 > M_2$, $M_1 \sim M_2$ or $M_1 < M_2$, though the asymmetry in the first case is slightly larger. We have checked that for these sets of parameters the mass of the lightest neutralino is about 40 GeV (for $\tan \beta \sim 3$) to 60 GeV (for $\tan \beta \sim 1$), and the second lightest neutralino has a mass of about 60 GeV to 80 GeV ; hence, these models are consistent with the MSSM models with scenarios motivated by current data [16]. The fact that the asymmetry is larger for smaller $\tan \beta$ can be understood as follows: First, because the Higgsino-top-stop coupling is proportional to $1/\sin \beta$, it becomes larger for smaller $\tan \beta$. Second, for small $\tan \beta$ (~ 1), $\tilde{\chi}_1^0$ is Higgsino-like and $\tilde{\chi}_2^0$ is gaugino-like for $M_1 \geq M_2$.⁴ (For $M_1 < M_2$, the properties of $\tilde{\chi}_1^0$ and $\tilde{\chi}_2^0$ are reversed.) Hence, we anticipate a larger asymmetry for a smaller $\tan \beta$ and $M_1 \geq M_2$. Furthermore, as anticipated, a lighter stop gives a larger parity nonconserving asymmetry through loop corrections. After choosing the sets of SUSY parameters that give the largest parity nonconserving effect, we found that the asymmetry \mathcal{A}_{EW} is positive and of the order of a percent. To observe such a small

³ This is motivated by the conclusion in Refs. [3] and [5] that $|\mathcal{A}|$ increases as $M_{t\bar{t}}$ increases.

⁴ Higgsino-like does not imply a hundred percent Higgsino component, etc.

effect, one needs at least 10^4 fully reconstructed $t\bar{t}$ pairs in the lepton plus jets decay channel, which is at the limit of what can be expected with 10fb^{-1} of luminosity at the Tevatron.

In the general mSUGRA model $\tan\beta$ can be much larger than 1. For larger $\tan\beta$ it was shown that the parity nonconserving asymmetry from the SUSY Yukawa contributions can be enhanced [5]. As indicated in Table 2, for the sets of SUSY parameters that give large parity nonconservation, the asymmetry \mathcal{A}_{EW} have the same sign as \mathcal{A}_Y . Also, \mathcal{A}_{EW} is larger than \mathcal{A}_Y for $\tan\beta \sim 1$, smaller for $\tan\beta > m_t/m_b$, and about the same for $\tan\beta \sim 3$. The sum of the asymmetries \mathcal{A}_{EW} and \mathcal{A}_Y is about one percent, and not sensitive to the detailed parameters of the SUSY models.

Recall that the SM prediction of the asymmetry \mathcal{A} , at the order m_t^2/v^2 , is about 0.36% for a 100 GeV Higgs boson [3, 5]. Since none of the asymmetries shown in Tables 1 and 2 is very large, being typically larger than a percent, we conclude that to observe the parity nonconserving asymmetry \mathcal{A} induced from the SUSY EW and SUSY Yukawa loop corrections predicted by the two classes of models discussed above will be challenging at the Tevatron with 10fb^{-1} of luminosity. However, because of the strong enhancement factor $1/\sin^2\beta$ coming from the square of the Higgsino-top-stop coupling [cf. Eq. (3)], the parity nonconserving asymmetry $|\mathcal{A}|$ can easily be much larger if $\tan\beta$ is significantly less than unity. Although this is not favored by either of the two classes of models considered above, it is in principle allowed in the MSSM. Another possibility that gives a large parity nonconserving asymmetry in the MSSM is to have not only a light stop but also a light sbottom; however, this is again not favored by either of the two classes of models discussed above. Finally, we show in Table 3 the predicted asymmetries for the SUSY models with $\theta_t = 0$ in which the left-handed top-squark is lighter than the right-handed one. In this case, the asymmetry \mathcal{A}_{EW} is negative while \mathcal{A}_Y is positive. Also, $|\mathcal{A}_{EW}|$ is larger than \mathcal{A}_Y for $\tan\beta \sim 1$, smaller for $\tan\beta > m_t/m_b$, and about the same for $\tan\beta \sim 3$. Hence, the contributions of \mathcal{A}_{EW} and \mathcal{A}_Y mostly cancel for $\tan\beta$ near 3.

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Table 1:

Parity nonconserving asymmetries in $p\bar{p} \rightarrow t\bar{t} + X$ for $M_{t\bar{t}} > 500$ GeV. The CM energy of the collider was assumed to be 2 TeV and its integrated luminosity 10 fb^{-1} . The other relevant SUSY parameters are $m_{\tilde{t}_2} = m_{\tilde{b}_1} = m_{\tilde{b}_2} = 500$ GeV, $A_t = -\mu \cot \beta$, $\theta_t = \pi/2$, and $\mu = -60$ GeV.

$\tan \beta$	M_1 (GeV)	M_2 (GeV)	\mathcal{A}_{EW} for $m_{\tilde{t}_1} = 50$ GeV (%)	\mathcal{A}_{EW} for $m_{\tilde{t}_1} = 90$ GeV (%)
1.0	50	100	1.25	0.92
	75	75	1.32	0.91
	100	50	1.31	0.92
1.5	50	100	0.89	0.61
	75	75	0.95	0.59
	100	50	0.96	0.63
2.0	50	100	0.76	0.50
	75	75	0.80	0.48
	100	50	0.82	0.49
3.0	50	100	0.66	0.42
	75	75	0.69	0.41
	100	50	0.71	0.41

Table 2:

Parity nonconserving asymmetries in $p\bar{p} \rightarrow t\bar{t} + X$ for $M_{t\bar{t}} > 500$ GeV. The CM energy of the collider was assumed to be 2 TeV and its integrated luminosity 10 fb^{-1} . The other relevant SUSY parameters are $m_{\tilde{t}_1} = 90$ GeV, $m_{\tilde{t}_2} = m_{\tilde{b}_1} = m_{\tilde{b}_2} = 500$ GeV, $m_{H^+} = 300$ GeV, $A_t = -\mu \cot \beta$, $\theta_t = \pi/2$, and $\mu = -90$ GeV.

$\tan \beta$	M_1 (GeV)	M_2 (GeV)	\mathcal{A}_{EW} (%)	\mathcal{A}_Y (%)	\mathcal{A} (%)
1	75	150	0.74	0.16	0.90
	100	100	0.72	0.16	0.88
	150	75	0.73	0.16	0.89
3	75	150	0.37	0.33	0.70
	100	100	0.35	0.33	0.68
	150	75	0.34	0.33	0.67
10	75	150	0.32	0.37	0.69
	100	100	0.30	0.37	0.67
	150	75	0.30	0.37	0.67
35	75	150	0.32	0.54	0.86
	100	100	0.30	0.54	0.84
	150	75	0.29	0.54	0.83

Table 3:

Parity nonconserving asymmetries in $p\bar{p} \rightarrow t\bar{t} + X$ for $M_{t\bar{t}} > 500$ GeV. The CM energy of the collider was assumed to be 2 TeV and its integrated luminosity 10 fb^{-1} . The other relevant SUSY parameters are $m_{\tilde{t}_1} = 90$ GeV, $m_{\tilde{t}_2} = m_{\tilde{b}_1} = m_{\tilde{b}_2} = 500$ GeV, $m_{H^+} = 300$ GeV, $A_t = -\mu \cot \beta$, $\theta_t = 0$, and $\mu = -90$ GeV.

$\tan \beta$	M_1 (GeV)	M_2 (GeV)	\mathcal{A}_{EW} (%)	\mathcal{A}_Y (%)	\mathcal{A} (%)
1	75	150	-0.58	0.16	-0.42
	100	100	-0.58	0.16	-0.42
	150	75	-0.57	0.16	-0.41
3	75	150	-0.28	0.33	0.05
	100	100	-0.26	0.33	0.07
	150	75	-0.25	0.33	0.08
10	75	150	-0.25	0.37	0.12
	100	100	-0.22	0.37	0.15
	150	75	-0.21	0.37	0.16
35	75	150	-0.24	0.54	0.30
	100	100	-0.22	0.54	0.32
	150	75	-0.21	0.54	0.33